Does entanglement depend on the timing of the impacts at the beam-splitters?

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February 1, 2008

A new nonlocality experiment with moving beam-splitters is proposed. The experiment is analysed according to conventional quantum mechanics, and to an alternative nonlocal description in which superposition depends not only on indistinguishability but also on the timing of the impacts at the beam-splitters.
Keywords: relativistic nonlocality experiment, timing-dependent entanglement.

1 Introduction

Entanglement is Schrödinger's name for superposition in a multi-particle system. In particular he called *entangled states* two-particle states that cannot be factored into products of two single-particle states in any representation. Multi-particle superposition is considered to be the characteristic trait of quantum mechanics [1]. If one cannot distinguish (even in principle) between different paths from source to detector, the amplitudes for these alternative paths add coherently, and multi-particle correlations appear. If it is possible in principle to distinguish, correlations vanish. Work by John Bell [2], by Daniel M. Greenberger, Michel A. Horne, and Anton Zeilinger [3], and by Lucien Hardy [4] pointed out that local-realistic theories cannot account for the two- and multiparticle correlations implied by the superposition principle. Local-realism is the name for Einstein's assumption that nothing in physical reality happens fasten than light. The quantum mechanical violation of local-realism is now mostly called nonlocality. In spite of the loopholes in the experiments [5], it is today largely accepted that superluminal nonlocality is a feature of nature: most physicists will not be surprised, if a future "loophole free" Bell experiment [6] definitely demonstrates the violation of the locality criteria (Bell's inequalities or others). Nevertheless nonlocality cannot be used by human observers for practical purposes (impossibility of "superluminal signaling"). Hence, if one accepts that relativity experiments like Michelson-Morley only imply a practical impossibility for man to communicate faster than light, no contradiction between these experiments and quantum mechanics arises.

However, the heart of relativity is the conclusion that there is no absolute spacetime, no "aether". Simultaneity depends on the observer's state of movement, the order of succession of two space-like separated events may change if one changes the inertial frame. Relativity of space-time seems to be at odds with the quantum mechanical assumption that superposition depends exclusively on indistinguishability [1, 6, 7], and not on the times at which the values are measured, in any inertial frame whatsoever. Consider for instance the orthodox quantum mechanical description of the perfect EPR correlations in two-particle experiments with entangled polarized photons: according to the superposition principle, the spin operator related to a measuring apparatus with two parallel oriented polarizing beam-splitters has two eigenvectors $|+1,+1\rangle$ and $|-1,-1\rangle$, representing two orthogonal quantum eigenstates; the measurement causes the entangled state to jump into either the state $|+1,+1\rangle$ or the state $|-1,-1\rangle$ instantaneously, where the first state means that both photons are detected in the detectors monitoring the transmitted output ports, and the second one that both photons are detected in the detectors monitoring the reflected output ports. Consequently, the measurement produces events which are simul-

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taneously strictly correlated in spacelike separated regions. But in which inertial frame are these correlated events simultaneous? Quantum mechanics does not answer this question. Moreover, because each measurement of polarization may lie outside the other's light cone (e.g. the two measurements may be spacelike separated events), the measurement which is considered as the cause of the "jump" in a certain inertial frame, is no longer the cause in another inertial frame. For one observer the value measured at side 1 depends on which value has been measured at side 2, and for another observer the value measured at side 2 depends on which value has been measured at side 1. Different observers are led to contradictory descriptions of the same reality. That is the resason why there still seems to be no consistent relativistic interpretation of the "quantum jump" (also referred to as "reduction of the wave packet" or "wavefunction collapse") associated with the measurement process, or why the notion of collapse appears to have no meaning in a relativistic context [8]. Such causality paradoxes have also motivated models that give up the relativity of spacetime and assume an absolute order of succesion or "quantum aether" [9].

Besides this conflict between relativity and quantum mechanics, we would like to highlight another problem more intrinsic to quantum mechanics itself. No matter if one accepts the relativity of space-time or quantum aether, the superposition principle seems to contradict somewhat another main postulate of orthodox quantum mechanics, namely "no values prior to measurement". According to this postulate, only after a specific measurement has been made can we attribute a definite physical property to a quantum system: there are no pre-existing values prior to the measurement, or, what is the same, the measurement creates the values. Therefore, the appearance of perfect nonlocal correlations necessarily express a link existing between *real* measured values, and one is led to assume that the measurement at one of the regions produces either a value $+1$ or -1 after taking into account the value that has *actually* been measured in the other region. This means that there is an order of succession, and thus the perfect correlations should disappear if the measurement in region 1 occurs, in the inertial frame of the analysing device in this region, *before* the measurement in region 2, and the measurement in region 2 occurs, in the inertial frame of the analysing device in this region, *before* the measurement in region 1. But even if one assumes a universal order of succesion and rejects the possibility two perform two "before" measurements, one has to admit the possibility of simultaneous measurements. For such a case it is absurd to assume *together* that photon 1 impacting at beam-splitter 1 chooses the output port taking account of the choice photon 2 has *really* made at beam-splitter 2, and photon 2 chooses taking account of the choice photon 1 has *really* made. Therefore, in the case of simultaneous measurements in absolut space-time, the perfect correlations should also disappear. The superposition principle looks, therefore, to be at odds not only with relativity, but also with the postulate of "no values prior to the measurement".

The purpose of this letter is to stress that quantum mechanics (QM in what follows) is a particular view of the relationship existing between superposition and indistinguishability, but that other views are possible. QM considers indistinguishability to be a *sufficient* condition for superposition. However, at the present time exclusively non-relativistic experiments without moving devices have been done. Stricktly speaking, such experiments support only the view that indistinguishability is a *necessary* condition for superposition. On this line of thinking we present in the following the basic features of an alternative nonlocal description which assumes that superposition does not depend exclusively on indistinguishability but also on the timing of the impacts at the beam-splitters. Furthermore we propose a relativistic experiment that may allow us to decide between this alternative view and QM.

2 Definitions and Principles of the Alternative Description (AD)

Consider the experiment with polarized photons sketched in Fig.1. Two classes of photon pairs, (H_1, H_2) and (V_1, V_2), are prepared through down-conversion in the "Bell state":

$$|\phi\rangle = \frac{1}{\sqrt{2}}(|H_1, H_2\rangle - |V_1, V_2\rangle) \qquad (1)$$

where H and V indicate horizontal and vertical polarization, respectively. The polarizing beam-splitters BS_1 and BS_2 are vertical oriented, and preceeded by half wave plates, which rotate the polarization of the photons by angles α, β. Suppose each beam-splitter can move fast, and change from one inertial frame to another.

The proposed AD is based on the following definitions and principles:

If it is in principle impossible to know to which input sub-ensemble of BS_i, $i \in \{1, 2\}$, a particle belongs by detecting it after leaving BS_i, then the impact at BS_i is referred to as originating indistinguishability or uncertainty, and labeled u_i. If it is in principle possible to know to which input sub-ensemble of BS_i a particle belongs by detecting it

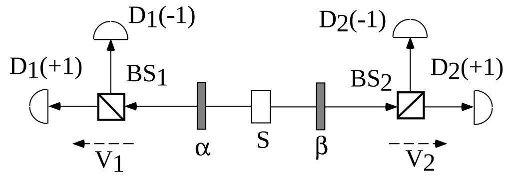

Figure 1: Experiment with polarized photons involving moving BS.

after leaving BS_i, then the impact at BS_i is referred to as making possible distinguishability, and labeled d_i.
At the time T_i at which a particle i arrives at BS_i, we consider whether in the inertial frame of this beam-splitter, particle j ($j \in \{1,2\}, j \neq i$) has already made a u_j impact or not, and introduce the following definitions:
Definition 1: the impact of particle i in BS_i is a *before* event b_i if:

1. it is a u_i, and
2. either the impact of particle j at BS_j is a d_j one; or $(T_i < T_j)_i$, the subscript i after the parenthesis meaning that all times referred to are measured in the rest frame of BS_i.

Definition 2: the impact of particle i in BS_i is a *non-before* event a_i if:

1. it is a u_i, and
2. the impact of particle j at BS_j is a u_j one, and
3. $(T_i \geq T_j)_i$.

We can now state the two principles of AD:
Principle I: if the impact of a photon i at BS_i is a b_i impact, then photon i produces values taking into account only local information, i.e., it is not influenced by the parameters photon j meets at the other arm of the setup.
Principle II: if the impact of a photon i at BS_i is a a_i impact, then photon i takes account of photon j in such a way that the values photon i actually produces, and the values photon j produces in a b_j impact are correlated according to the superposition principle.
Assuming *Principle I* and *Principle II* we implicitly *discard* the hypothesis that the values produced by a particle, say photon 1, depend on the state of movement of the detectors D_1. Effective, the experimental data suggest that the outcome distribution does not depend on the distances at which the detectors are placed with respect to the beam splitters [10]. This is also in accord with the quantum mechanical formalism. It is reasonable, therefore, to assume that the value produced by photon 1, if it is detected after leaving splitter BS_1 and there is no other splitter between BS_1 and the detector, is determined at the time the photon leaves the splitter (certainly, as far as the photon is not detected, it is always possible for the physicist to let the photon pass to a further interferometer and to oblige it to change the outcome distribution). We *discard* also the hypothesis that the values produced by photon 1 depend on the time at which photon 2 impacts at a detector D_2, because there is experimental evidence against it [11].

3 Consequences

We begin by introducing some notation: an experiment e will be labeled by indicating the kind of impact that each particle undergoes, f.i. $e = (a_1, b_2)$. Expressions like $P(e_{\sigma\omega})$, $\sigma, \omega \in \{+,-\}$, denote the probabilities to obtain the indicated detection values in experiment e (i.e., photon 1 is detected in $D_1(\sigma)$, photon 2 in $D_2(\omega)$). In a similar way, we write $P^{QM}(e_{\sigma\omega})$ for the probabilities predicted by standard QM for experiment e (note that in this case the impacts can only be u_i or d_i, since QM doesn't consider differences in timing).
Principle II implies that

$$P((a_1, b_2)_{\sigma\omega}) = P((b_1, a_2)_{\sigma\omega}) = \\ = P^{QM}((u_1, u_2)_{\sigma\omega}). \qquad (2)$$

In all interference experiments performed till now both splitters were at rest, and one of the impacts did happen always before the other. Then, according to Equation (2), AD reduces to QM for all experiments already done.
On the other side, it follows from *Principle I* that

$$P((b_1, b_2)_{\sigma\omega}) = P^{QM}((d_1, d_2)_{\sigma\omega}) = \\ = P^{QM}((u_1, d_2)_{\sigma\omega}) = P^{QM}((d_1, u_2)_{\sigma\omega}). \qquad (3)$$

Experiments in which both impacts are *non-before* events, or in which the photons impact succesively in several beam-splitters, as well as the generalization to n-particle experiments are discussed in other articles.
Suppose now that the state of movement of the beam-splitters implies the following situation: The impact at BS_1, in the inertial frame of BS_1, occurs before the impact at BS_2, and the impact at BS_2, in the inertial frame of BS_2, occurs before the impact at BS_1. The diagram in Fig.2 corresponds to such a *gedanken Experiment*: It is assumed that the photons are channeled from the source to the beam-splitters by means of optical fibers, and that the optical path S-BS_2 traveled by photon 2, is a

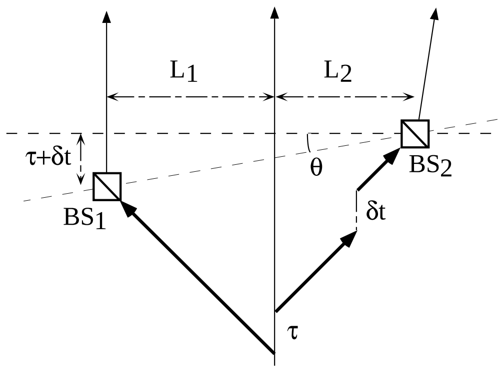

Figure 2: Experiment with one moving BS: time diagram in laboratory frame.

bit longer than optical path S-BS_1 traveled by photon 1. The delay in time resulting from this path difference is labeled δt. At the moment photon 1 arrives at BS_1, this splitter is at rest, at a distance L_1 from the source. At the moment photon 2 arrives at BS_2, this splitter is at distance L_2 from the source and moving with velocity V in the indicated direction. The delay between the emissions of the two photons is labeled τ.

As said, the quantum formalism does not depend at all on the inertial frames of the beam-splitters. The correlation coefficient is assumed to be given by the Lorentz-invariant expression [2, 5]:

$$E = \sum_{\sigma,\omega} \sigma\omega P^{QM}((u_1, u_2)_{\sigma\omega}) = \cos 2(\alpha + \beta). \quad (4)$$

Consequently, for $\alpha + \beta = 0$, QM predicts perfectly correlated results (either both photons are transmitted, or they are both reflected).

Principle I implies that each photon produces values according to local information only, and equation (3) leads to a correlation coefficient

$$E = \cos 2\alpha \cos 2\beta. \quad (5)$$

Consequently, according to AD, $\alpha + \beta = 0$ does not imply $E = 1$. In particular, if $\alpha = -\beta = 45°$ one gets $E = 0$, i.e. the four possible outcomes $(+1, +1)$, $(+1, -1)$, $(-1, +1)$, $(-1, -1)$ equally distributed.

In summary, for the *gedanken Experiment* of Fig.2, QM (according to which indistinguishability is a sufficient condition for superposition) and AD (according to which superposition does also depend on the timing of the impacts at the splitters) lead to clearly conflicting predictions.

4 Possibility of a real experiment

What about the possibility of doing a real experiment allowing us to distinguish between the two descriptions? The condition, guaranteeing that the impact of photon 2 at BS_2 occurs in the inertial frame of BS_2 *before* the impact of photon 1 at BS_1, can be easily derived from the diagram of Fig.2:

$$\tan\theta = \frac{V}{c} = \frac{c(\tau + \delta t)_{max}}{L} \quad (6)$$

where V is the velocity of BS_2, c is the speed of light, $L = L_1 + L_2$ and $(\tau + \delta t)_{max}$ is the maximal delay between the two impacts. For photon produced by down-conversion, $\tau << \delta t$, so equation (6) imposes the following condition to the value of δt:

$$\delta t < \frac{VL}{c^2}. \quad (7)$$

Velocities of about 100 m/sec (360 km/h) can be reached by setting BS_2 on a fast moving wheeler (note that, according to AD, detectors don't need to move). Bell-experiments with over 4 km of optical fiber have been done [12]: an experiment with such a value for the distance L between the beam-splitters would allow us an upper limit for parameter δt of 4.4 ps. A quantum channel of 24 km, has already been achieved [13]: an experiment with such a value of L would allow us an upper limit for δt of 26.4 ps. The ongoing effort to achieve quantum cryptography over long distances, may make possible values of L greater than 100 km in near future, which would mean that δt could reach values of 111 ps. The feasibility of the relativistic experiment depends, therefore, basically on the capability to ensure a significant number of impacts respecting such limits for δt. Work to clarify whether the control of the setup's geometry can be implemented to this extent with reasonable effort is in progress.

5 Conclusion

In conclusion, the nonlocality of quantum mechanics is so important and counterintuitive that as many experiments as possible should be performed to get deeper insight in its nature. If the proposed relativistic experiment with moving beam-splitters can be carried out and the results uphold the predictions of the conventional superposition principle, then it will be hard to maintain the belief of the "pacific coexistence" between relativity and quantum mechanics. Then models giving up relativity of space-time like Bohm's causal model [9], should be explored more in depth. On the contrary, if

the results of the experiment with moving beam-splitters prove to be in conflict with quantum mechanics, the road to a new description of physical reality would be opened. This description would base on two main assumptions: (1) there are in nature faster than-light-influences which cannot be used by man for superluminal signaling, and (2) superposition depends not only on indistinguishability but also on the timing of the impacts at the beam-splitters. Such a description would be perfectly coherent with both, quantum nonlocality and space-time relativity. The realization of experiments allowing us to investigate time orderings different of the conventional ones appears promising in any case [14].

Acknowledements

We acknowledge Anton Zeilinger (University of Innsbruck) for discussions about possible experimental realizations. A. Suarez acknowledges support of the Leman and Odier Foundations.

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